frontiers | Frontiers in Ecology and Evolution

TYPE Original Research
PUBLISHED 11 January 2023
DOI 10.3389/fevo.2022.1092636

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Conservation and Restoration Ecology, a section of the journal Frontiers in Ecology and Evolution

RECEIVED 08 November 2022
ACCEPTED 21 November 2022
PUBLISHED 11 January 2023

CITATION
Adil M, Zhang C, Yao Z, Lu S, Qin Z, Wang J, Mahmood A, Riaz MW and Lu H (2023) Interactive effects of intercropping and mulching under conservation tillage as sustainable agriculture increased cotton productivity.
Front. Ecol. Evol. 10:1092636.
doi: 10.3389/fevo.2022.1092636

Interactive effects of intercropping and mulching under conservation tillage as sustainable agriculture increased cotton productivity

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Climate change poses a significant risk to food security. Recent floods in Pakistan could serve as an example. In the current climate change scenario, there is a dire need to develop methods that increase crop productivity and reduce the threat of food insecurity in areas with low crop production. A detailed field experiment was conducted to check the effects of intercropping and straw mulching under conventional tillage (CT) and no tillage (NT) systems on soil health indicators and cotton productivity at the experimental area of Khwaja Fareed University of Engineering and Information Technology (KFUEIT), Rahim Yar Khan, Pakistan. The main plot treatments comprised CT and NT. The subplot treatments were sole cotton (C1), cotton + mung-bean intercropping (C2), cotton + mung-bean + straw mulching (C3) and cotton + straw mulching (C4) under CT, while sole cotton (N1), cotton + mung-bean intercropping (N2), cotton + mung-bean + straw mulching (N3) and cotton + straw mulching (N4) were the NT subplot treatments. Overall, NT increased plant height by 18.4 %, chlorophyll a and b contents by 28.2 and 21.1%, respectively, mean boll weight by 17.9%, and seed yield by 20.9% compared to CT ($P < 0.05$). The interaction of tillage and mulching increased plant height by 7.0% under CT and 21.8% under NT in comparison with no mulching. Similarly, straw mulching under NT increased chlorophyll a and b contents by 41.9 and 28.5%, respectively, mean boll weight by 26.9%, and cotton seed yield by 23.0% in comparison with no mulching under NT. Intercropping decreased crop yield without straw mulching but increased it under straw mulching. Further, straw mulching increased soil physicochemical properties under NT, which contributed to increasing crop productivity. We concluded that straw mulching under NT might be a promising practice for enhancing cotton yield, productivity, and soil health in low-productivity areas.

KEYWORDS

cotton-mung bean intercropping, straw mulching, conservation tillage, soil health, crop productivity, climate change

Introduction

The cotton crop, scientifically known as *Gossypium hirsutum* L., is cultivated throughout the world and is known as "white gold" (Puspito et al., 2015). It is an economically important crop that generates 600 billion USD annually (Shuli et al., 2018). The textile industry in Pakistan is dependent on cotton production, and Pakistan has great importance due to its large-scale cotton production every year; this places the country in the fourth position globally after India, China, and the USA on a global scale [Government of Pakistan (GOP), 2018]. Pakistan produced nearly 12 million bales on 2,699,000 ha, which helped raise the GDP by 1% through the agriculture sector (Ibrahim et al., 2008). On the other hand, Pakistan is among the most vulnerable countries that are highly susceptible to climate change events (Mehmood et al., 2022). Different factors, such as poor seed management, soil infertility, water scarcity, and expensive field treatments, play a major role in declining cotton yield and quality (Abdullaev et al., 2007).

Countries such as the Middle East and Australia face soil problems because of land changes, deforestation, and climatic conditions that have more detrimental effects in arid and semiarid conditions (Nosrati and Collins, 2019; Zeraatpisheh et al., 2020). Future strategies may focus on developing land for the agriculture sector within the populations of different communities without depleting natural resources (Broman and Robèrt, 2017). Sustainable agriculture is a fundamental part of making long-term plans for land development, as these strategies have low environmental hazards and better crop production (Busby et al., 2017). Sustainable agriculture is eco-friendly, less expensive, and protects the habitats that ensure security and conservation for plant and animal lives (Yadav et al., 2018). Soil microbial management (Jousset, 2017), minimum tillage (Singh et al., 2016), prevention of soil erosion (Bowers et al., 2020), soil fertility management, cover cropping, and intercropping are the main soil management practices (Martin-Guay et al., 2018; Sharma et al., 2018).

Agronomic factors such as tillage operating mechanisms, unsafe irrigation networks, and different seeding practices cause a reduction in crop production and quality (Farooq et al., 2020). Intense tillage practices to grow cotton deplete soil fertility and texture, resulting in poor crop production (Saharan et al., 2019). Soil erosion, nutrient depletion, and a lower water-holding capacity of the soil are all the results of single-crop repetition and traditional tillage techniques (Ryken et al., 2018). Enhancement of long-term crop production and yield depends upon conservation tillage that helps to improve soil quality (Martin-Guay et al., 2018). Previous studies revealed that conservation tillage techniques are suitable for arid and semiarid conditions where crop production is low, as these techniques help enhance phosphorus, nitrogen, potassium, and organic matter availability in the soil (Busari et al., 2015; Bhatt, 2017). Recent research suggested and proved conservation tillage is one of the fundamental and essential factors in increasing soil nutrients and soil quality (Duggan et al., 2005; Sayed et al., 2020). Long-term conservation tillage application boosts soil fertility by increasing micro soil biota (Page et al., 2020; Saha and Bauddh, 2020). Moreover, adding green mustard as manure increases organic matter accumulation in the roots of xerophytes in arid areas (Koishi et al., 2020).

Similarly, intercropping and cover cropping are advised for better quality and crop production, along with ensuring biodiversity restoration in an eco-friendly environment (Brussaard et al., 2007). Intercropping with leguminous plants is helpful for improving the economy, as these are cash crops and play a role in crop production (Baritz et al., 2018). Moreover, legumes have an important symbiotic relationship with nitrogen fixation bacteria, as the bacteria make root nodules, and they convert atmospheric nitrogen into different, useable forms by plants, which is called "biological nitrogen fixation." This useful relationship enhances soil fertility and crop production (Fustec et al., 2010). It also helps mitigate the danger of soil erosion (Hauggaard-Nielsen et al., 2008), enhancing moisture retention in the soil (Ghanbari et al., 2010), improving soil fertility (Hauggaard-Nielsen et al., 2009), and improving nutrient cycling and soil conservation (Chalka and Nepalia, 2006; Lithourgidis et al., 2011). Legume intercropping is a famous methodology for improving soil fertility and health, and many studies have described intercropping as the best strategy to increase the physical aspects of soil in recent years (Srinivasarao et al., 2012; Lal, 2015). We hypothesize that intercropping with straw mulching will improve cotton productivity and soil health under conservation tillage compared to the conventional tillage method.

Materials and methods

Site characteristics and climatic conditions

A short-term field experiment was conducted at an experimental area of Khwaja Fareed University of Engineering and Information Technology (28.4075 N, 70.3053 E, 86 m above sea level), Rahim Yar Khan, Pakistan, during the summer of 2022. The experimental site was located in a plain area with an arid climate under irrigated conditions. Long-term climatic data were taken from the district agricultural extension department by Rahim Yar Khan and are shown in Figure 1. Before conducting field experiments, < 15 and 15–30 cm deep soil samples were taken from each corresponding experimental unit and accurately analyzed to determine the different physicochemical properties of the soil profile. The physicochemical properties of the experimental site are given in Table 1.

Experimental details

The field experiment was laid out in a split-plot design under a randomized complete block design (RCBD) with three replications. The experiment comprised two tillage systems with a legume intercrop and straw mulching (32 experimental units): CT= conventional tillage, wheat residues incorporated; NT = no tillage, wheat residues retained; C1 = sole cotton; C2 = cotton + mung bean; C3 = cotton + mung bean + straw mulching, and C4 = cotton + straw mulching under conventional tillage. Similarly, N1 = sole cotton, N2 = cotton + mung bean, N3 = cotton + mung bean + straw mulching, and N4 = cotton + straw mulching under no-tillage. The plot size was 18 m^2 (6 m * 3 m), and each plot was separated from the others by a distance of 0.5 m.

Direct drilling of seedlings was used to plow NT plots. The current experiment used the CT plots from the long-term cropping pattern. In the CT system, experimental plots were prepared by plowing with a conventional disc harrow to a depth of 30 cm before being properly planked the soil to mix the wheat crop residues. However, NT plots had cotton seeds sown directly on the tilled soil after harvesting wheat by retaining 30–50% of the wheat crop residues. Weeds were manually pulled away. On April 20, 2022, the cotton variety CIM-573 was seeded with a tractor-mounted Kharif drill at a seed rate of 15 kg ha^{-1}.

Additionally, the cotton crop was intercropped with a cover crop (mung bean variety NM-2016) 20 days after sowing. A basal application of 90 kg ha^{-1} of P, 60 kg ha^{-1} of K, and one-third of the necessary nitrogen dose (total of 160 kg ha^{-1}) was made at the planting time. The remaining N was divided into three equal portions, each weighing 35.6 kg ha^{-1} and applied at the first, third, and fifth irrigations. The canal water was used to irrigate the crops at the designated irrigation schedule stages (the first irrigation was done 20 days after sowing and subsequent irrigations at 10–15 days intervals depending upon weather conditions and crop requirements). The initial soil parameters of each plot were assumed to be the same.

Measurements and analytical procedures

Phenological, physiological, and yield attributes of the cotton crop

The chlorophyll content was calculated using a chlorophyll meter (SPAD-502; Minolta, Tokyo, Japan). The mean boll weight (MBW) was measured by randomly selecting 10 bolls from each experimental plot, and plant height was measured from the base to the tip of the main stem. The seed cotton yield (kg ha^{-1}) was calculated by multiplying the seed cotton yield (kg/plot) from the net plot area with the seed cotton weight from the 10 previously harvested bolls.

$$\text{Seed yield (kg/ha)} = \text{Seed yield (kg/plot)} \times 10,000\text{m}^2 / \text{Net plot area (m}^2\text{)} \quad (1)$$

Plants were taken from a 1 m^2 area at maturity to measure the total biomass. The collected samples were sun-dried until the weight remained constant. Using the conversion factor, the sample dry weights were then converted to biomass (kg ha^{-1}). Furthermore, the following formula was used to calculate the harvest index (HI) given by Sharma and Smith (1986).

$$\text{Harvest index (\%)} = \text{Seed yield (kg ha}^{-1}\text{)} / \text{Biological yield (kg ha}^{-1}\text{)} * 100 \quad (2)$$

Determination of soil physicochemical properties

Five soil samples from each experimental unit (<15 and 15–30 cm depths) were taken and examined for the various physicochemical characteristics of soil in accordance with standard operating procedures. A saturated soil paste was made to measure the soil pH, and electrical conductivity and pH and electrical conductivity meter were measured using a pH meter and electrical conductivity meter, respectively. The soil samples were dried and put through a 2-mm mesh filter. Wet oxidation was used to assess the organic matter in the soil (Walkley and Black, 1934). The amount of N, P, and K present in the soil was calculated by using the alkaline potassium permanganate (Subbiah and Asija, 1956), sodium bicarbonate (Olsen, 1954), and ammonium acetate (Nelson and Heidel, 1952).

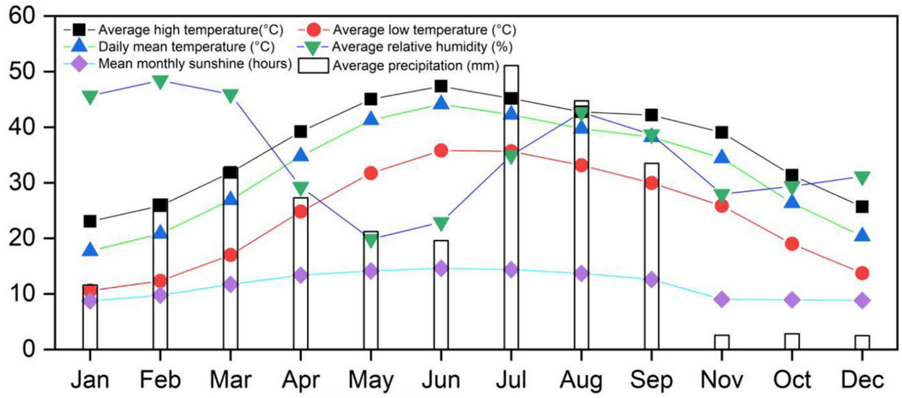

FIGURE 1
Long-term weather data (average high and low temperature, daily mean temperature, average relative humidity, mean monthly sunshine hours, and average precipitation at the experimental area.

TABLE 1 Soil physicochemical properties of the experimental site at cotton sowing and harvest under conventional tillage (CT) and no-tillage (NT) methods.

	Depth cm	ECe dS/m	pH	Organic matter (%)	AP (ppm)	AK (ppm)	Saturation %
At sowing							
CT/NT	<15	3.36	7.8	0.63	7.1	348	36
	15–30	2.55	7.8	0.56	4.2	215	38
At harvest							
CT	<15	3.35 a	7.7 a	0.66 b	7.3 b	349 b	36 b
	15–30	2.55 a	7.8 a	0.58 a	4.2 b	218 ab	39 ab
NT	<15	3.30 b	7.7 a	0.69 a	7.7 a	355 a	39 a
	15–30	2.51 b	7.8 a	0.58 a	4.4 a	219 a	40 a

Numbers followed by different letters within a column are significantly different at $P \leq 0.05$ by the least significance difference test.

Statistical analysis

For the statistical analysis, analysis of variance (ANOVA) was utilized for each of the study's parameters. To further differentiate differences between treatment means at a $p \leq 0.05$ as a significant threshold, Tukey's honestly significant difference (HSD) test was performed (Steel et al., 1997).

Results

Effect of management practices on plant height

The effects of intercropping and straw mulching on cotton plant height varied significantly under CT and NT. Figure 2 designates the effects of intercropping and straw mulching on cotton plant height under CT and NT. NT overall increased plant height by 18.4 % compared to CT ($P \leq 0.05$). The interaction of tillage with mulching and intercropping indicated significant impacts on plant height, such as straw mulching under CT (C4), which increased plant height by 7.0% compared to CT control (C1). Similarly, straw mulching under NT (N4) increased plant height by 21.8% compared to NT control (N1). However, intercropping decreased plant height by 7.2% under CT but increased it by 4.1% under NT compared to their respective control treatments. Mung bean intercropped with cotton under straw mulching (N3) increased plant height under NT ($P \leq 0.05$) but remained non-significant under CT (C3) (Figure 2).

Effect of management practices on chlorophyll contents

The effects of intercropping and straw mulching on cotton chlorophyll contents varied significantly under CT and NT, with NT significantly increasing chlorophyll a and chlorophyll

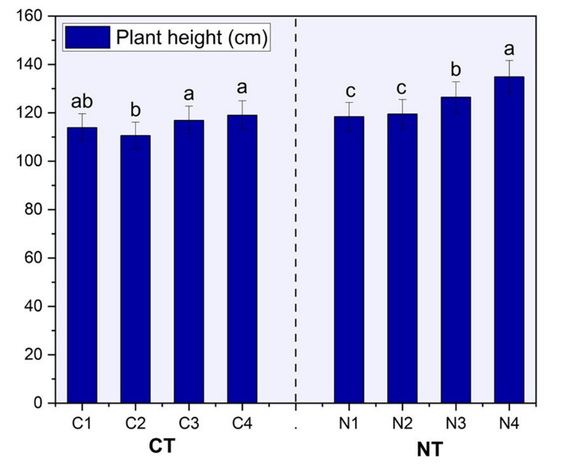

FIGURE 2
Interactive effect of intercropping, mulching, and different tillage systems on plant height. Different letters above graph bars indicate significant differences $p \leq 0.05$).

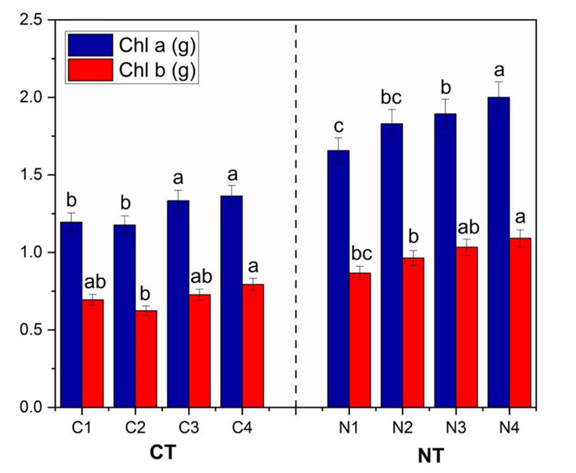

FIGURE 3
Interactive effect of intercropping, mulching, and different tillage systems on chlorophyll a (Chl a) and chlorophyll b (Chl b) contents. Other letters above graph bars indicate significant differences at $p \leq 0.05$).

b contents by 28.2 and 21.1%, respectively, compared to CT (Figure 3; $P \leq 0.05$). The interaction of tillage with mulching and intercropping indicated significant impacts on chlorophyll contents, such as straw mulching under CT (C4), which increased chlorophyll a and chlorophyll b by 16.8 and 7.7%, respectively, compared to control (C1). Similarly, straw mulching under NT (N4) increased chlorophyll a and chlorophyll b by 41.9 and 28.5%, respectively, compared to NT control (N1). However, intercropping under CT (C2) decreased chlorophyll a and chlorophyll b contents by 3.2 and 8.2%,

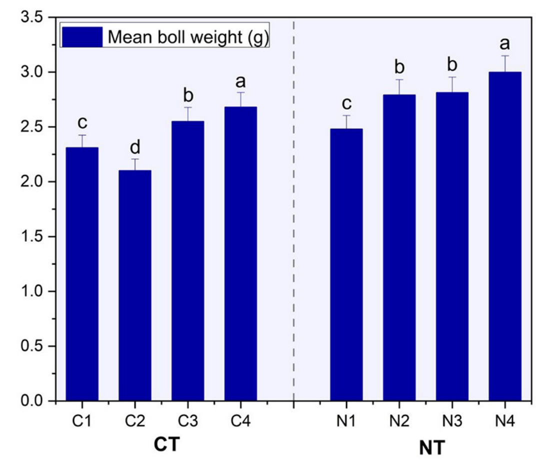

FIGURE 4
Interactive effect of intercropping, mulching, and different tillage systems on the mean boll weight of cotton. Other letters above graph bars indicate significant differences at $p \leq 0.05$).

respectively, compared to control C1. In contrast, intercropping under NT (N2) increased chlorophyll a and chlorophyll b by 24.9 and 17.2%, respectively, compared to control N1. Mung bean intercropped with cotton with the application of straw mulching (C3) significantly increased chlorophyll a and chlorophyll b contents by 14.8 and 9.5%, respectively, compared to C1. Similarly, N3 significantly increased chlorophyll a and b contents by 21.8 and 16.5%, respectively, compared to N1.

Effect of management practices on mean boll weight

The effects of intercropping and straw mulching on cotton mean boll weight varied significantly under CT and NT. Figure 4 shows the effect of intercropping and straw mulching on cotton for mean boll weight under CT and NT. NT significantly increased mean boll weight by 17.9% compared to CT (C1) ($P \leq 0.05$). The interaction of tillage with mulching indicated significant impacts on mean boll weight, such as straw mulching under CT (C4), which increased mean boll weight by 21.0% compared to CT control (C1). Similarly, straw mulching under NT (N4) increased cotton mean boll weight by 26.9% compared to NT control (N1). However, intercropping under CT (C2) decreased mean boll weight by 13.1% compared to control (C1) but increased it by 17.7% under NT (N2) compared to control N1. The mung bean intercropped with cotton with the application of straw mulching (C3) increased mean boll weight by 12.4% and, under N3, by 21.1% compared to their control treatments.

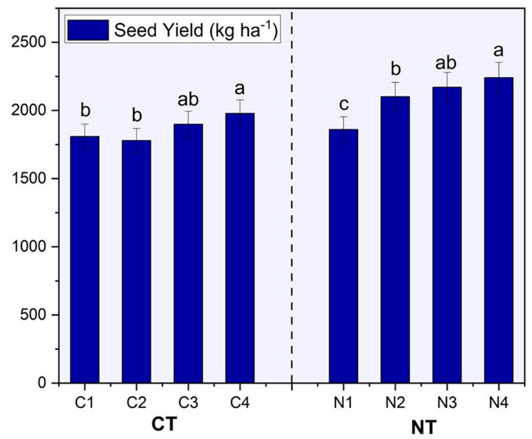

FIGURE 5
Interactive effect of intercropping, mulching, and different tillage systems on cotton seed yield. Other letters above graph bars indicate significant differences $p \leq 0.05$).

Effect of management practices on seed yield

The effects of intercropping and straw mulching on cotton seed yield varied significantly under CT and NT, such that NT significantly increased seed yield by 20.9% compared to CT ($P \leq 0.05$) (Figure 5). The interaction of tillage with mulching indicated significant impacts on seed yield, such as straw mulching under CT (C4), which increased seed yield by 12.9% as compared to CT control (C1), while straw mulching under NT (N4) increased seed yield by 23.0% as compared to NT control (C4). However, intercropping decreased seed yield by 4.1% compared to control C1 under CT but increased it by 20.7% under NT compared to control N1. Mung bean intercropped with cotton under straw mulching significantly increased seed yield by 8.4 and 9.1% under NT and CT, respectively. Moreover, NT increased the harvest index (HI) by 0.6% compared to CT.

Soil health indicators

Indicators of soil health such as soil organic matter (SOM), pH, ECe, and soil available P and K are summarized in Table 1. The employment of diverse tilling methods, legume intercrops, and mulching had a significant impact on these indicators. NT enhanced soil organic matter by 9.52%, available potassium (AK) by 2.0%, available phosphorous (AP) by 8.45%, and saturation percentage by 8.33% in < 15 cm of soil. NT enhanced soil organic matter by 3.57%, available potassium by 1.86%, available phosphorus by 4.76%, and saturation percentage by 5.26% in the top 15–30 cm of the soil layer. However, NT decreased soil ECe by 1.36% in < 15 cm and 1.57% in 15–30 cm of soil.

There was a strong correlation between mulching, legume intercropping, soil health indices, and a couple of modes of tillage. There was a positive Pearson relationship between soil organic matter, soil availability of phosphorus and potassium, seed production, biological yield, and harvest index (Figure 6).

Discussion

The overall phenological stages were smoothly completed by the cotton crop grown under NT, with the results showing better overall production under NT than CT. It is comparable to the earlier cotton study conducted using conservation tillage (Qamar et al., 2015). In comparison with the CT system, the NT system under straw mulching displayed greater values for the physiological characteristics of the cotton crop (Figures 2–5), as determined in earlier studies such as those described by Chakraborty et al. (2010), who compared no mulching to straw mulching and found that it increased crop yield by 13–25%, which might be because of the strongest root growth and development that strongly accounted for higher physiological characteristics and greater assimilation partitioning (Rajpoot et al., 2018).

In this study, a stronger connection between tillage and mulching was discovered for cotton physiological and yield parameters, such as crop yield, which increased with NT straw mulching compared to other combinations (Figure 5). This suggests that residue cover or reduced tillage with NT can store more soil moisture by reducing rainfall water loss and soil surface evaporation, which ultimately increases crop yield (Wang et al., 2011; Adil et al., 2022a,b). According to Wang et al. (2018), straw mulching enhanced precipitation storage efficiency by 13–16% compared to no mulching. Wheat production and soil water content both increased by 23%, while water usage efficiency (WUE) improved by 33% because of straw mulching (Zhang et al., 2015). Similarly, compared to no mulching, straw mulching increased crop grain yield by 13–25% (Chakraborty et al., 2010). According to numerous studies, a traditional tillage strategy improves the morphological and yield characteristics of the cotton crop in the first few years (Dhima et al., 2007). However, under NT, the yield of seed cotton increased because of enhanced soil porosity (Table 1 and Figure 6) (Qamar et al., 2015) and increased water use effectiveness (Rahman et al., 2018).

Due to favorable soil and other environmental factors, the sole cotton crops, C1 and N1, had better phenological traits (Figures 3–5) and recorded better physiological qualities than cotton-mung bean intercropping. This is due to the absence of competition for light, space, water, and nutrients, which promotes rapid growth and development and better phenological characteristics (Paul et al., 2013). Moreover, NT had appreciable variations in the current outcomes, such as higher plant height, mean boll weight, and seed cotton

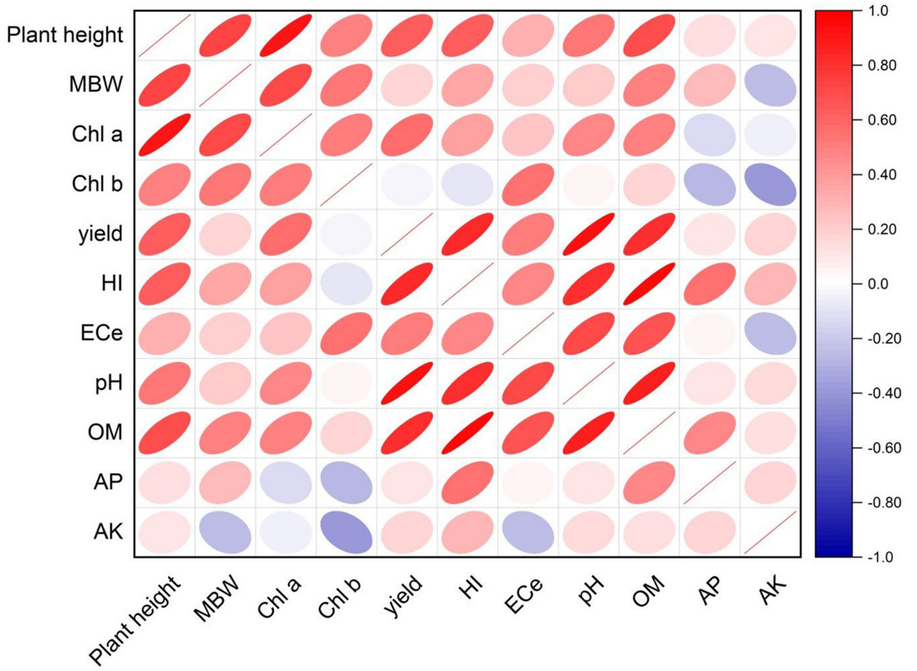

FIGURE 6
Correlation of growth, yield, and physiological attributes of the cotton crop, yield components of legume intercrops, and soil health indicators under different tillage systems and legume intercrops; the areas of circles show the absolute value of corresponding correlation coefficients tested at the * 0.01 significant level. PH, Plant height; TB, Total bolls per plant; MBW, Mean boll weight; Chl a, chlorophyll a; Chl b, chlorophyll b; Yield, seed cotton yield; HI, harvest index; ECe, electrical conductivity; pH, soil pH; OM, organic matter; AP, soil available phosphorus; AK, soil available potassium.

yield compared to CT, which significantly improved the morphological, yield, and yield-related characteristics of the cotton crop. This improvement may be attributable to higher root penetration into the soil and higher nutrient (N, P, and K) uptake to meet the needs of the cotton crop's growth (Ahmad et al., 2021).

According to our research, legume intercrops decreased plant height, total bolls per plant, and mean boll weight, which may be attributed to the competition for nutrients and water, space, and sunlight between cotton and mung bean, as previous studies reported decreased crop yield with cover cropping compared to no cover cropping in the first year of study (Zhang et al., 2015), instead of their ability to fix nitrogen (Chalka and Nepalia, 2006). The cover crops also tend to decrease ET (Adil et al., 2022a,b). The reason could be that lower soil water due to competition between cotton and mung bean could result in a less accessible soil moisture supply to the crop, reducing water evaporation from the soil surface and restricting crop transpiration, which could be the cause of the lowered ET caused by cover crops (Zhang et al., 2007).

In the present study, legume intercropping cultivated under the NT system had higher seed yield, higher biological output, and a higher harvest index compared to the CT system. Furthermore, it is clear that identical results under NT were reported in prior studies, such as Hou et al. (2012), who reported noticeable changes in crop production between conservation and conventional tillage systems. The grain yield improved with NT compared to CT by 9.6%, which might be due to improved soil physical and chemical characteristics that have been reported in previous studies (Fabrizzi et al., 2005). The reason could be that there is reduced soil disturbance, enhanced aggregate stability, and increased water-holding capacity under conservation tillage compared to conventional tillage (Hillel, 1998). Furthermore, these processes are beneficial for conserving soil water during crop planting, protecting against brief droughts during the growing season, and boosting crop yield (Pikul and Aase, 2003; Verhulst et al., 2011).

Another factor controlling the results is the fertilizer application; crop yield may have increased due to the effective application of nitrogen under perfect seedbed conditions for ideal growth and development (Hauggaard-Nielsen et al., 2008; Ahmad et al., 2016). The most recent results of the experiment indicated that mung-bean intercropped with cotton set better values for yield and yield-related qualities, which might be because these beans are grown under ideal conditions for mung-bean growth and had higher nitrogen fixation (Ahmad et al., 2020). A possible solution that preserves soil health indicators in arid climates is conservation tillage (Bhatt, 2017), as it increases the amount of organic matter, phosphate, and potassium in the soil, which eventually improves soil health indicators (Duggan et al., 2005; Sayed et al., 2020). Additionally, soil organic matter, available soil phosphorus, and potassium were higher with NT due to better soil quality indices (Table 1). Similar results for greater soil organic matter under NT and leguminous intercropping were obtained in previous studies (Page et al., 2020; Saha and Bauddh, 2020).

Conclusion

There was a need to develop methods that help increase crop production under the current climate change scenario in low-productivity areas. We wanted to assess the interactive effects of possible management practices on the current area, such as the previous crop production, which was totally dependent on conventional tillage. The current study indicated that straw mulching under conservation tillage performed better in terms of phonological, physiological, morphological, and yield attributes. However, soil analysis revealed that no-tillage and leguminous crop intercropping improved soil health indicators. Moreover, the interaction of tillage, leguminous crop, and mulching showed a better response on seed yield and harvest index. However, intercropping decreased cotton yield, which might be due to the competition for the uptake of nutrients, including water; however, the effect was antagonistic under straw mulching. In conclusion, no-tillage and straw mulching could be recommended for achieving higher cotton crop productivity. More long-term research and field studies are needed to raise awareness of no-tillage and the role of leguminous crops in nitrogen fixation and sustaining soil health in cotton-growing areas.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

HL, MA, CZ, ZY, SL, ZQ, and JW conceived the research and review, drafted the manuscript, and finalized it. AM and MR helped improve the draft by providing valuable suggestions and information. All authors contributed to the article and approved the revised version.

Funding

This study was under the auspices of NSFC 42071267, the Program for Innovative Research Team (in Science and Technology) with the University of Henan, Henan Province (21IRTSTHN008), and the Scientific and Technological Research Projects in Henan Province (222102320472).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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